

**IO'S INTERACTION WITH THE JOVIAN MAGNETOSPHERE.** C. T. Russell, *Institute of Geophysics, University of California, Los Angeles, CA 90095-1567*; F. Bagenal, *APAS Dept., University of Colorado, Boulder, CO 80309-0391*; A. F. Cheng, *APL/JHU, 1110 Johns Hopkins Rd., Laurel, MD 20723-6099*; W-H. Ip, *MPAe, Postfach 20, Katlenburg-Lindau, D-3791, Germany*; A. Roux, *C.E.T.P., 0-12 Avenue de l'Europe, 78140 Velizy, France*; W. H. Smyth, *Atmospheric and Environmental Research, Inc., 840 Memorial Drive, Cambridge, MA 02139*.

Io is the most volcanically active object in the solar system. It sits in the solar system's most intense radiation belt, orbiting the planet with the most rapid spin and the strongest magnetic field. Many unique features are associated with Io and its interaction with the Jovian magnetosphere as the data gathered by Galileo on December 7, 1995 revealed.

Io first called attention to itself through its control of decametric wavelength radio emissions. Early attempts to explain this control assumed that Io was a highly electrically conducting object whose motion through the Jovian magnetic field would lead to electrical potential drops, particle acceleration and a field-aligned current system coupling Io to the Jovian ionosphere. The force generated by the electrodynamic interaction is in the direction to speed up Io in its orbital motion and to slow down the rotation of the Jovian ionosphere. The magnetic flux tube that threads Io thus plays a critical role in the coupling of Io and Jupiter. Since Io's orbital motion is not in synchronism with Jupiter's spin, the Io flux tube slips with respect to Jupiter and/or Io. Such slippage may result in an electric field parallel to the magnetic field that accelerates charged particles along the magnetic field as occurs in the auroral regions on Earth. If Io were a poor conductor with no ionosphere and a non-conducting crust, a terrestrial Moon-like interaction would occur in which plasma would hit the moon and be absorbed but in which little distortion of the magnetic field would occur. When Voyager 1 flew within 11 Io radii south of Io, it detected a magnetic field distortion consistent with the expected current for a perfectly conducting obstacle, about  $3 \times 10^6$  A, and the former model became generally accepted. Since Galileo passed through the Io wake in almost the plane of symmetry of the interaction, it cannot as easily constrain the size of these currents.

The story is more complicated, however, than the simple picture of a conductor moving through a magnetic field. Io is surrounded by a corona and extended neutral gas cloud and a plasma torus produced by the interaction of the magnetospheric particles with Io and its atmosphere. The magnetospheric particles corotate with Jupiter, because of their electrical connection to the ionosphere along the magnetic field, and hence stream past Io at 57 km/s. If a neutral particle from Io's corona and extended neutral gas cloud becomes ionized in this flowing, magnetized plasma, it will immediately begin to drift with the background magnetized plasma, and gyrate around the magnetic field (with a velocity equal to its drift velocity). The momentum gained by the "picked up" ions is extracted from Jupiter's angular momentum via field-aligned currents. Mass and momentum loading can lead to a greater integrated field-aligned current than the conducting sphere situation. If many particles are picked up in the flow, the flow initially slows down according to momentum conservation, and the drift velocity and gyration velocity of newly created ions

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will be smaller. Thus on streamlines far from Io we expect the greatest temperatures of the newly created ions (270 eV and 540 eV for oxygen and sulfur ions) and the fewest picked up particles. On streamlines closest to Io, the picked up ions should be densest and coldest. We expect that a small fraction of the incident magnetic flux tubes are not deflected to the sides around Io but slowly flow across the region of field lines that are connected to Io. These flux tubes become heavily mass loaded and, when they exit the Io flux tube proper, they form a dense cold wake behind Io. This expectation is consistent with the Galileo ion measurements and the inferred electron density pointing to a cold, near stagnant "ionosphere" in the center of the wake. Just outside the cold wake the average ion temperature is about  $360 \pm 90$  eV as expected for pickup at the corotational velocity of 57 km/s. Inside the wake the average temperature is consistent with pickup at velocities at least a factor of 6 slower. Eventually, downstream from Io we expect that magnetic forces would restore the slowed wake plasma to the corotational speed of the plasma torus but would not necessarily heat it. Far from Io, but at the same radial distance from Jupiter, Voyager saw typical densities of  $2000 \text{ ions cm}^{-3}$  consisting of oxygen and sulfur ions with temperatures of about 100 eV. Galileo passed through a torus of similar composition and temperature but one twice as dense. We attribute this density change to an increase in mass loading by Io.

Since the ions are picked up perpendicular to the magnetic field, their initial angular distribution is ring-shaped about the magnetic field. In general, this is a very unstable configuration and ion cyclotron waves are expected to grow and scatter the particles in pitch angle so that they are more isotropically distributed about the magnetic field. Indeed strong ion cyclotron waves were found by Galileo in the region around Io extending outward to  $16 R_{\text{Io}}$  and inside of Io's orbit to  $6.5 R_{\text{Io}}$ . We note that the growth of waves in a multi component plasma such as at Io is complicated and we do not expect growth associated with the gyrofrequencies of all the picked-up ions, but rather only the heavier ones. Finally at near relativistic ion energies Io acts as a sink of particles rather than a source but in absorbing these highly energetic particles atoms and ions are sputtered from the surface and the atmosphere enhancing further the mass loading.

In summary we find that ions are added to the existing torus in a volume around Io, the ions flow around Io, and a cold wake region forms downstream. Waves arise to scatter the particles and the magnetic field is twisted away from its Jovian orientation. However, the magnitude of these effects exceeded our previous expectations. The plasma was denser and colder than expected and the waves stronger. Field-aligned beams of electrons, while expected, were only expected to be unidirectional, not bi-directional. We note that neither Galileo nor Voyager 1 entered the Io flux tube itself, the one that links the moon with Jupiter's ionosphere. It is conceivable that electron beams there are even more intense than the bidirectional electron beams seen by Galileo.